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RADIATION FORMATION OF A NON-VOLATILE CRUST

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ABSTRACT

Ion irradiation of the outer meters of a cometary surface produces new molecular species in the solid state. Because of the vacuum interfaces these segregate in an irreversible way into a non-volatile residue and new very volatile species, which are lost directly or lost when the comet enters the inner solar system. It is, therefore, likely that a comet exposed to background radiations in the Oort cloud would obtain an outer web of nonvolatile material which will lead to the formation of a substantial 'crust' ($\sim 10^2$ gm/cm^2). Except for fizzures and break-off of pieces due to warming of subsurface gases, this mantel should be continuously hardened for a periodic comet due, primarily, to thermal processing. There will also be active regions which were shaded from the cosmic ray radiation.

Keywords: Comet Crust, Radiation Modification

1. INTRODUCTION

The recent observations of the nucleus of P/Halley indicate that it has a very low albedo and the gas and dust primarily effuse from very localized regions. If the volatile material is assumed to have been distributed fairly uniformly throughout the nucleus when the comet was formed then the recent observations would imply that there are large regions in which the nucleus has acquired a thermally stable 'crust' with a tensil strength sufficient to contain the internal subliming gas pressures. Alternatively, the nucleus may be very heterogeneous with the non-active regions containing primarily rocky, meteoritic materials. In this note we describe a scenario consistent with the first possibility. In this model radiation-induced changes in the outer layers are responsible for the creation of a thermally stable 'crustal' material prior to entry into the inner solar system. Here, we first review the radiation effects on cometary materials and then describe the mantel formation process.

2. RADIATION MODIFICATIONS

By now it is well established that ionizing radiations (UV, x-rays, γ-rays, electrons, fast ions) produce alterations in low temperature molecular solids such as condensed gases and organics. This primarily results in the formation of radicals (bond breaking) during the electronic relaxation processes. Knowledge of this process has been used by a number of authors to describe the likely alterations in cometary and precometary materials (Refs. 1-3).

At the extremely low temperatures in the Oort cloud individual radicals can, in principle, be stored for considerable periods. During the warming-up of irradiated materials having a high density of stored radicals produced by ionizing radiations, a number of experimental programs have shown that radical recombination is induced resulting in an enhanced volatility (Refs. 1,2,4). Therefore Whipple, Donn (Ref. 5) and others proposed that, if the outer layers of the comet were modified by ionizing radiations, a fresh comet could be active at rather larger than expected distances from the sun, consistent with observations. The storage of a high density of radicals requires extremely small diffusion coefficients and/or large recombination barriers as the radical and its parent are generally not displaced many lattice distances. That is, annealing of the broken bonds can in principle occur prior to the formation of new more volatile species. Such effects need to be examined for Oort cloud temperatures and those temperatures in the interior of an evolved comet when considering transient releases of material. On the other hand, if the local density of excitations is high, as in the 'track' of a fast ion or as in the 'spurs' associated with secondary electrons produced by energetic electrons, ions or photons, 'permanent' alterations are directly produced. These permanent alteraions have been shown to have, in addition to radicals, both very volatile and involatile components if the materials contain carbon or sulfur atoms. For example, irradiation of organics results in the formation of carbon residues *and* the production of H_2, O_2, CO, etc. (Ref. 6).

Recent experiments have roughly quantified the radiation precipitation of residues. Moore et al. (Ref. 1) have shown that an interstellar ice mixture (H_2O, NH_3, CH_4) forms a residue (of the order of 1%) after a dose of only 10 eV molecule. In pure materials, such as CO and SO_2, a small fraction (of the order of a few percent) of the material is converted into a residue (Refs. 7-9) after somewhat higher doses, whereas in H_2S, CS_2 (Ref. 10) and CH_4 (Refs. 11-13) most of the material is converted into a residue ($\sim$ 100 eV/mol). Lanzerotti et al. (Ref. 14) have studied the sample thickness dependence and ionization density effect on residue formation in condensed CD_4. They find a competition between the rate of polymerization and the rate of film erosion in very thin condensed samples.

Besides the condensed gases all organics are readily carbonized while releasing volatiles and producing black residues (Refs. 6,12,15). Such processes occur efficiently under particle radiation due in part to the enhanced diffusion initiated by the incident ions. These processes produce a segregation in the material, after long exposure, with the less volatile residue accreting into a porous condensed material (Ref. 14), and the more volatile species brought to the vacuum interface or stored in the large defects and pores in the solid. Such materials can also contain unreacted radicals depending on the thermal history.

In pure water ice, of course, although the material becomes porous on irradiation, (Ref. 16) residue formation does not proceed as O_3 and H_2O_2 are the largest oxygen species. Therefore, at very low temperatures, the irradiated H_2O remains a stable mix of radicals and molecules.

3. COMET SURFACE ALTERATION

A number of authors (Refs. 1-5,17) have discussed the implications of the fact that the outer layer of a comet, exposed to cosmic rays in the Oort cloud, receives a considerable dose of radiation over the long storage times. This presumably occurs in a fluffy porous object which is composed of grains containing particles that are already highly processed (Ref. 4). Therefore, the comet is a mixture of ices and organics with a much smaller silicate component, based on the Greenberg model of grains. (Not only are the ices and organics susceptible to the radiation processes even the silicates may be somewhat modified (Ref. 18)).

Cosmic ray ions deposit their energy in the material of interest by direct ionization and by inducing nuclear reactions. For GeV ions the mean nuclear reaction length ($\sim$ 70 gm/cm^2) dominates the stopping of these ions (Ref. 19). The nuclear products also eventually dissipate their energy either directly or indirectly to ionization. According to Draganic et al. (Ref. 17) at a depth of one meter in a *non-porous* icy object (therefore many meters in a porous aggregation of grains) every molecule would have received an average of > 40eV of energy in 4.6 x 10^9 years. This dose increases rapidly with decreasing depth due to the larger flux of lower energy ions, although the total dose in the outer layers depends on the model assumed for these lower (< 1 GeV) energy ionizing particles. Draganic et al. (Ref. 17) also estimate the doses of radiation due to radioactive decay which occurs throughout the comet. These doses are an order of magnitude smaller, producing corresponding smaller amounts of material alterations.

In carbon and sulfur containing materials significant residue formation can occur at the cosmic ray doses associated with the first equivalent meter of material of a comet. The amount of alteration will depend on the material composition as discussed above. The residues so produced have been shown to be porous, locally compacted, filimentary materials that are stable at room temperature (Refs. 1,15, and 16). At the low temperatures of the Oort cloud, the external and internal surfaces of the porous residues, made from the irradiated organics and ices, would be coated with volatile molecular species. Most H_2 presumably would diffuse out of the porous surface at these temperatures, with some trapped in defects and bubbles. These materials would also contain some radicals.

The levels of ion irradiation given above are also sufficient to enhance adhesion (Ref. 20) between the new non-volatile residues, the modified organics, and the silicate grain cores. Therefore, after a long residence period in the outer solar system we imagine the comet to have a 'crust' with a web-like construction of refractory materials. Because the comet is not a smooth sphere, but rather a locally irregular aggregation of a weakly compacted material we imagine this 'crust' does not cover all regions exposed to the vacuum. That is, there are numerous large cracks, crevices, and shadowed surfaces with relatively pristine material.

On warming of the above object the radicals will react and the very volatile gases in the porous 'crust' will quickly be lost leaving a dark residue depleted in volatiles which covers a more volatile underlying material. This final picture is much like the picture described by Fanale and Salvail (Ref. 21) produced by thermally enhanced adhesion and volatile depletion. In the present model the much more extensive volatile-depleted, mantel formation is initiated by, or at least highly enhanced by, the radiation hardening processes described above. In addition there are active 'surface' regions which were not exposed to the cosmic ray flux. In these regions thin crusts will temporally form after each release of material (Ref. 20).

The subsequent warming of the dark 'crust' will continue the depletion of volatiles in this region and complete the radical recombination and residue formation process. It will only slowly conduct heat into the underlying regions partially depleting the volatiles below the porous 'crust' (Ref. 21). This process would form a rather thick outer mantel and gas ejection would come preferentially from regions lacking a thick mantel. However, with a sufficiently rapid thermal increase on close approach, the radiation initiated 'crust' may be broken, releasing volatiles and giving a cometary burst which would also contain large amounts of dark refractory debris and, possibly, reactive material depending on the thermal history of the interior (Refs. 1,2 and 4). In those regions in which the mantel survives, the continuous thermal compaction, and additional ionizing radiations, will act to harden this 'crust'. For the grains ejected from active regions subsequent modification occurs due to the locally produced plasma and, eventually, solar particles (Refs. 3,22).

4. SUMMARY

That some radiation processing of cometary material has occurred is suggested by the depletion of H and the significant percent of carbon and sulfur in a refractory form. Further, this refractory material is often fragile and under dense, consistent with the expectations for a radiation processed organic material (Ref. 15). This processing may have been produced in the grains prior to accretion due to UV photon and cosmic ray bombardment, a shock in the interstellar medium, or in the early period of the formation of the solar system (Ref. 23).

The process of radiation induced alteration of the outer meters of a comet in the Oort cloud, however, is certain to occur. This results in the formation of more volatile molecular species and the precipitation of new refractory materials when carbon or sulfur atoms are present as organics or condensed molecules. This can, in principle, account for the enhanced volatility of new comets, the formation of a dark, thermally stable 'crust', and the existence of locally active regions. The principle question that needs to be answered is the degree of formation and the ability of the mantel to survive the heating produced on entering the inner solar system. However, this problem pertains to all models that begin with a mixture of ices and refractory materials. In the present model the cosmic ray irradiation process significantly enhances the ability to form a rather thick mantel of refractory material.

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